Plio–Pleistocene time evolution of the 100-ky cycle in marine paleoclimate records

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To constrain theories for the dynamical evolution of global ice mass through the late Neogene, it is important to determine whether major changes in the record were gradual or rapid. Of particular interest is the evolution of the near 100-ky ice age cycle in the middle Pleistocene. We have applied a new technique based on multiple taper spectrum analysis which allows us to model the time evolution of quasi-periodic signals [Park and Maasch, 1992]. This technique uses both phase and amplitude information, and enables us to address the question of abrupt versus gradual onset of the 100-ky periodicity in the middle Pleistocene.

The variation of climate proxy variables at a given frequency f_o (with associated period $T_o = 1/f_o$) can be parameterized by $\Re\{A(t)e^{-2\pi i f_o t}\}$, a sinusoid with a slowly-varying amplitude $A(t)$. The function $A(t)$ is complex-valued, allowing slow variations in phase as well as magnitude. We define $A(t)$ as the 'envelope' of the signal at 'carrier frequency' f_o. If $A(t) = A_o$ is a constant, the signal is termed 'periodic' or 'a phase-coherent sinusoid.' If $A(t)$ varies, the signal is termed 'quasi-periodic.' All methods of determining the envelope of a quasi-periodic signal have shortcomings. Bandpass filters, such as those used by Ruddiman et al [1989], cannot model discontinuities in the envelope of a quasi-periodic signal, and thus, are of little help in discriminating between a sudden and a gradual onset for the 100-ky ice age cycle. Moreover, a narrow bandpass in the frequency domain requires a long time-domain filter, so that a significant number of data points at the ends of the series must be discarded. Similarly, the choice of length for the overlapping data segments in the Ruddiman et al [1986b] analysis involves a tradeoff between frequency and time resolution.

We apply instead a more flexible approach based on multiple-taper spectrum analysis [Thomson 1982; 1990; Park et al. 1987, Berger et al 1991]. The multitaper

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approach allows the analyst to model the envelope function $A(t)$ using the tools of linear inverse theory, solving for the envelope function that fits the time series data while optimizing some property of the envelope. Inversion algorithms can be derived that find the 'smallest' and 'smoothest' envelopes that fit spectral 'data' from a given time series [Park 1990; Park 1992]. Special cases of these the algorithms can be derived to model sudden changes in the envelope. This allows us to examine the abruptness of the onset of the 100-ky periodicity as well as the evolution of the obliquity and precession signals. The estimation procedure relates spectral estimates at f_o, using a set of orthogonal Slepian data tapers, as linear functionals of an unknown envelope $A(t)$, so that the envelope is constructed from a linear combination of the Slepian tapers. Since the Slepian tapers are optimally bandlimited, multitaper envelope estimation can be thought of as an extremely sharp narrow-band filter valid for the entire duration of the series.

The shortcomings of the algorithm we use are similar to those of other linear inverse problems. For instance, the multitaper envelope estimation procedure can model envelope discontinuities, but the technique cannot by itself discriminate between continuous and discontinuous models for the 100-ky cycle, since envelopes of both types can be constructed that fit the spectral 'data' exactly. The analyst must use other, perhaps subjective, criteria for choosing among models that fit the data. This nonuniqueness is a common problem in linear inverse theory; in principle an infinite number of envelopes can fit a finite number of spectral data exactly. In most cases, the *a priori* constraint that the signal at a carrier frequency f_o have a 'slowly-varying' envelope, except at one or more specified time points, reduces greatly the number of acceptable models for the envelope, and motivates the solution of a 'smoothest' envelope that fits the spectral data.

We investigated the time-evolution of the 100-ky cycle in $\delta^{18}O$ data, thought to reflect global ice-volume variations. We analyzed $\delta^{18}O$ data from DSDP Site 607 and ODP Site 677, from which three long (> 2.6 My) time series have been published [Shackleton and Hall, 1989; Ruddiman et al 1986ab; 1989; Raymo et al 1989]. We find evidence for a coherent $\delta^{18}O$ signal for both cores in the eccentricity and obliquity frequency bands, consistent with variations in global ice volume as the causative factor. However, the nature of the earth system response to orbital insolation cycles depends on the time scale adopted in the spectral analysis. If the Ruddiman/Raymo time scale for DSDP Site 607 is accepted, the $\delta^{18}O$ obliquity cycle has enhanced amplitude between 1.0 and 1.5 Ma, relative to the late Pleistocene ($t < 1.0$ Ma), and a nonlinear response of the earth system to orbital obliquity is inferred (Figure 1). If the Shackleton et al [1990] time scale for ODP Site 677 is accepted, the amplitude match between the $\delta^{18}O$ obliquity cycle and the 65°N insolation derived by Berger and Loutre [1991] from the recent astronomical solution of Laskar [1988; 1990] is very good for times $t \lesssim 2.3$ Ma (Figure 2). (The phase match for obliquity is enhanced by the fact that the data series were tuned to the astronomical time series, so that the observed phase agreement is not surprising.) The veracity of the ODP 677 time scale therefore correlates with a linear earth-system response to orbital obliquity.

Based on our analysis of data from these two deep-sea cores, we do not find compelling evidence for an abrupt change in the 100-ky $\delta^{18}O$ signal. Rather, envelope inversions in the eccentricity band suggest that the 100-ky $\delta^{18}O$ cycle is phase-locked with the 124-ky eccentricity cycle some 300-400 ky prior to its late-Pleistocene growth in amplitude and phase-lock with the 95-ky eccentricity cycle (Figure 3). An abrupt change in the 95-ky envelope near 0.85 Ma is consistent with DSDP 607 data on the Ruddiman/Raymo time scale, but such a transition would occur while leaving the 124-ky envelope largely unchanged. If the Shackleton et al [1990] time scale for ODP 677 is accepted, our three $\delta^{18}O$ records are consistent with a low-amplitude 100-ky cycle between 1.2 and 2.6 Ma, whose local period of oscillation alternates between the two major eccentricity periods at 95 and 124 ky. The phase of these 100-ky oscillations prior to 1.2 Ma is related to the phase of the astronomical eccentricity cycles where the cycles have significant amplitude. The match between the precessional envelopes of Sites 607 and 677 is poor, when both are expressed in terms of the Shackleton et al [1990] time scale. Climate simulation studies suggest that cyclic salinity changes in equatorial surface waters are a plausible contributor to the ODP 677 $\delta^{18}O$ data in the precessional band, and could explain this discrepancy. However, our time-rescaling of data from DSDP 607, using visual isotope-stage matching, may not be precise enough to transform the short-period precession cycles with sufficient accuracy.

Further study of more paleoclimate records will be necessary in order to address more fully the time-evolution of the 100 kyr cycle. For instance, the correlation of $\delta^{18}O$ signals from Sites 677 and 607 is intriguing, but comprehensive tests for the global coherence of $\delta^{18}O$ signals should use data from more than two sites. The phase information contained in the paleoclimate records may reaffirm the notion that external earth-orbital forcing could be the pacemaker of the ice age cycles. However, the mid-Pleistocene amplitude increase of the quasi-periodic 100-ky $\delta^{18}O$ signal awaits a complete explanation, which appears to depend on factors other than orbital insolation changes.

Future Tasks:

1) Collection of climate proxy data series, with good time control, from both deep-sea, lake-bed, and land-based sedimentary sequences. Much data probably lies dormant in the older cores stored by the Ocean Drilling Program, but only the older

cores often suffer from coring gaps that impede detailed time series analysis. Newer core data are spliced from parallel-paired drill cores at a single location.

2) careful cross-spectral analysis of different data series to investigate how the earth climate system, as a whole, responded to orbital insolation cycles over the past 2–3 My, the period of Earth history most relevant to current global change problems. The techniques developed for the above project can be extended to cross-series studies. The buzzword for this kind of study is 'global teleconnections,' the manner in which climate at different parts of the globe interacts. The response of climate to modest changes in its boundary conditions can (in principle) be tracked by its response over individual Milankovitch cycles.

3) similar analysis of data series from earlier periods of Earth history e.g. the Cretaceous and the Eocene. Data is accumulating for a significant response to orbital cycles, but a global synthesis has only been attempted so far with numerical climate models. The Earth's climate was warmer in these two periods, but our understanding of how the Earth sustained such temperature is, at best, incomplete. Many studies point towards higher carbon dioxide levels as a causative factor, and the ubiquitous Milankovich-driven limestone/black-shale sequences suggest big changes in ocean circulation. Are the Cretaceous and Eocene global climates a picture of what awaits us in a greenhouse future?

4) Despite a decade of global-warming predictions based on numerical climate models, it must be admitted that these models (global circulation, energy balance, etc) can represent the earth's climate dynamics only in a crude manner. The features of the climate system that are critical to its longer-term variation (decades and centuries) may not be apparent with the current generation of numerical climate models. Improving the global circulation models is a high priority. This includes atmospheric, ocean and coupled atmosphere-ocean models.

5) Collection of a long-term global climate database to 'validate' the output of global circulation models. Such data are essential to check if the numerical climate models are working. Comparisons of atmospheric GCM results with satellite data have begun, but I am not aware of a global data-validation of oceanic GCMs.

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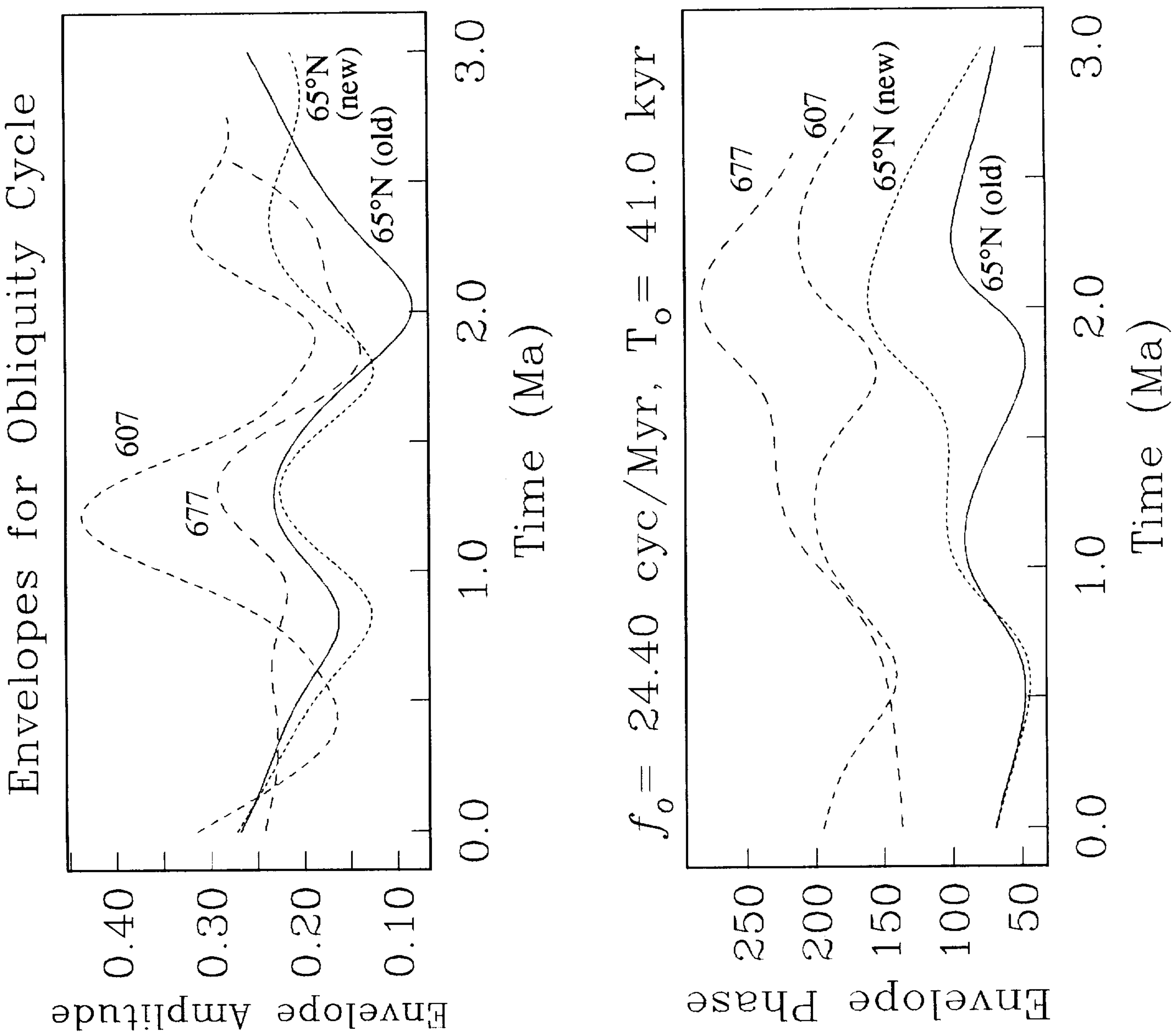
Figure Captions

Figure 1. Envelope inversions for the time-evolution of the 41-ky signal in the benthic $\delta^{18}O$ series from DSDP Site 607 and ODP Site 677, plotted against similar analyses for the astronomical insolation series derived from Berger [1978] ('65° old') and Berger and Loutre [1991] ('65°N new'). Seven 4π-prolate Slepian eigentapers are used to constrain the estimates, using 'smoothness' penalty function (10). The amplitude units in this and succeeding plots are parts-per-thousand $\delta^{18}O$. Note the phase correlation (with a constant shift) between the older astronomical series and data from DSDP Site 607, and the correlation between the newer astronomical series and data from ODP Site 677. This arises from the orbital tuning performed on the data series. Orbital tuning does not enforce correlations between envelope amplitudes, as is evident from the upper panel.

Figure 2. Similar to Figure 1, but with the envelope of the Berger [1978] series omitted and benthic $\delta^{18}O$ data from DSDP Site 607 expressed in terms of the Shackleton et al [1990] time scale. Seven 4π-prolate Slepian eigentapers are used to constrain the estimates, using a 'smoothness' penalty function. Note the phase correlation (with a constant shift) between the data series. Note the improved correlations between envelope amplitudes in the upper panel.

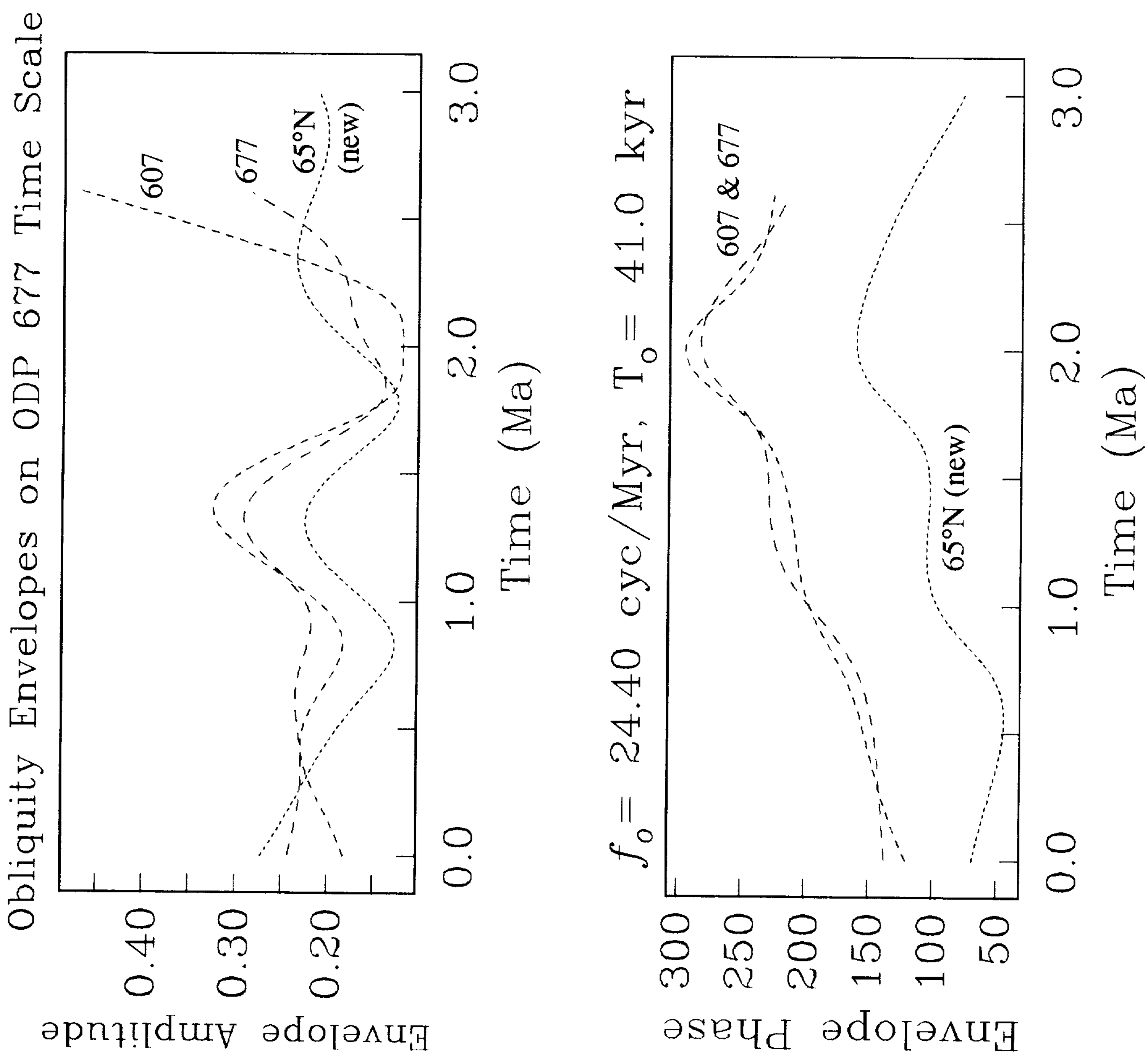
Figure 3. Test for the abrupt onset of the 100-ky signal. Double-line envelope inversion for the benthic $\delta^{18}O$ series from DSDP Site 607 on its published time scale, at the two major eccentricity quasi-periods of 95 and 124 ky. Seven 4π-prolate Slepian eigentapers are used to constrain the envelopes, which are constrained to be smooth everywhere except at t_o =0.85 Ma.

Figure 1



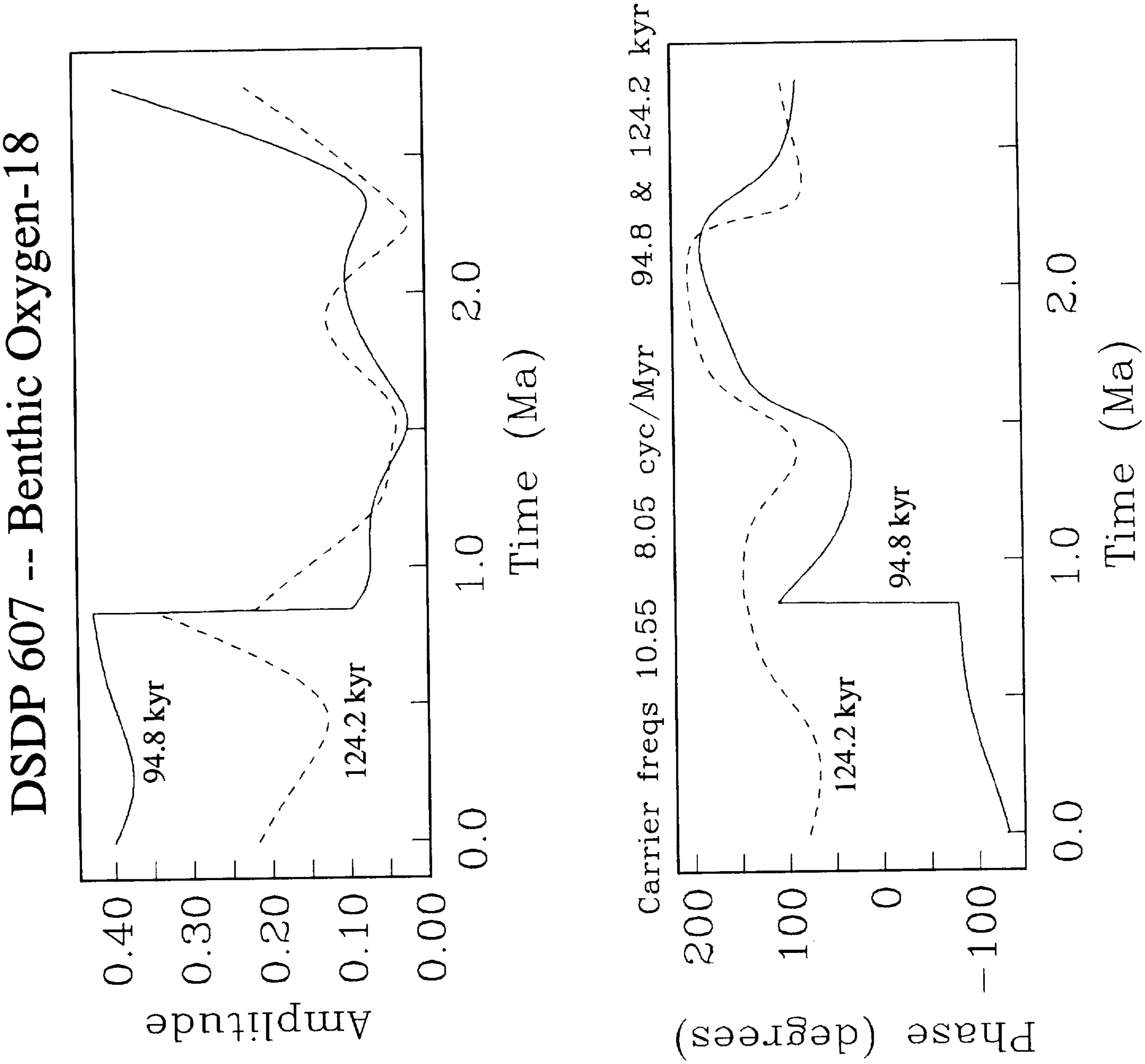
Envelopes for Obliquity Cycle
Envelope Amplitude
0.40
0.30
0.20
0.10
607
677
65°N (new)
65°N (old)
0.0
1.0
2.0
3.0
Time (Ma)
f_o = 24.40 cyc/Myr, T_o = 41.0 kyr
Envelope Phase
250
200
150
100
50
677
607
65°N (new)
65°N (old)
0.0
1.0
2.0
3.0
Time (Ma)

Figure 2



Obliquity Envelopes on ODP 677 Time Scale
Envelope Amplitude
0.40
0.30
0.20
607
677
65°N (new)
0.0
1.0
2.0
3.0
Time (Ma)
f_o = 24.40 cyc/Myr, T_o = 41.0 kyr
Envelope Phase
300
250
200
150
100
50
607 & 677
65°N (new)
0.0
1.0
2.0
3.0
Time (Ma)

Figure 3



DSDP 607 -- Benthic Oxygen-18
94.8 kyr
124.2 kyr
Amplitude
0.40
0.30
0.20
0.10
0.00
0.0
1.0
2.0
Time (Ma)
Carrier freqs 10.55 8.05 cyc/Myr 94.8 & 124.2 kyr
Phase (degrees)
200
100
0
−100